The Vaporizing Liquid Micro-Thruster:
Proof of Principle and Preliminary Thermal Characterization

Juergen Mueller[*], Indrani Chakraborty[**], David Bame[+], and William Tang[++]

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

A microfabricated **vaporizing liquid thruster** was constructed and succesfully tested for the first time. In this liquid-fed thruster concept, aimed at providing attitude control for microspacecraft, propellant vaporization is achieved in a microfabricated thin film heater arrangement. Propellant can be stored compactly as a liquid, reducing leakage concerns as well. Several thruster chips were tested using water as a propellant. The test set-up was a simple bench-top experiment, aimed at demonstrating proof-of-concept of the device. Complete vaporization was achieved at power levels as low as 2 W, with required thruster voltages seldomly exceeding 3 V, being as low as 2 V in some cases, thus fitting well within future microspacecraft capabilities. Proper heater channel design and packaging were found to have significant impacts on thruster performance.

resists jet
micro electromechanical system
MEMS

1. INTRODUCTION

Recently, a strong interest in micropropulsion devices capable of delivering very small thrust values and impulse bits at engine sizes and masses orders of magnitude smaller than available with current technologies[1], has developed within the space community. Within the National Aeronautics and Space Administration (NASA) as well as the Air Force, the reason for this interest can be found both in the drive to explore microspacecraft designs[2], typically viewed as spacecraft having wet masses on the order of 1-20 kg, as well as in the need for fine attitude control of larger spacecraft, such as those envisioned for future NASA space interferometry missions[3], for example.

One of the most challenging aspects of both types of missions, microspacecraft and interferometry, is attitude control. Either due to the low mass of the microspacecraft, or the stringent pointing and positioning requirements of spacecraft used in interferometry constellations, very small impulse bits will be required, which could reach into the 1 - 10 micro-Newton-sec range. The ability

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[*]Advanced Propulsion Technology Group, Senior Member AIAA.
[**]MEMS Group, Micro Devices Laboratory
[+]Propulsion Flight Systems Group
[++]Supervisor, MEMS Group, Micro Devices Laboratory

to provide very small impulse bits may also open up additional applications for micropropulsion devices, such as fine attitude control on more standard spacecraft buses eliminating the use for reaction wheels commonly employed for this task. Since these wheels can be heavy and may consume high levels of power, replacing them with a batch of microfabricated thruster clusters may result in net spacecraft weight and power savings, in particular if a propulsion system is already onboard the spacecraft for coarse attitude control or trajectory corrections, allowing the micro-thruster system to be plummed into the existing system.

While there is available today propulsion hardware able to deliver very small impulse bits, namely pulsed plasma thrusters (PPT) or Field Emission Electric Propulsion (FEEP) devices, these thruster types may not fit every mission need. In view of microspacecraft applications, for example, micro-thrusters will not only be required for fine-pointing, but are also needed to perform slew maneuvers. Depending on slew rates, required thrust levels for these maneuvers may reach well into the milli-Newton range, achievable with FEEP and PPT thrusters only at relatively high power levels and large engine sizes. There also exists the need for thrusters using non-contaminating propellants, in particular in constellation flying applications where there exists the possibility that thrusters firing on one spacecraft may be pointed directly towards another spacecraft in the constellation, possibly leading to contamination concerns.

A new micropropulsion concept, termed the Vaporizing Liquid Micro-Thruster[4,5] (VLM), was recently introduced, aimed at providing attitude control for spacecraft. This thruster concept is characterized by very small obtainable thrust values and impulse bits at extremely low thruster weight and size. Work on the VLM is in its earliest stages, as characterized by the work presented in this paper. Initial focus of this study is the determination of the feasibility of this thruster concept, to be followed by the determination of its performance and operating characteristics in future work. This paper, after introducing the VLM design concept, will discuss recent proof-of-concept testing, which lead to the vaporization of water propellant inside the chip in a laboratory bench-top set-up. Initial observations of basic thermal operating characteristics of the thruster will also be reported upon and different heater designs, and their impact on propellant vaporization,will be discussed.

II. CONCEPT

The Vaporizing Liquid Micro-Thruster concept, in its current configuration, relies in its construction on silicon-based microfabrication (MEMS - Microelectromechanical Systems) methods and is shown in Fig. 1. A completed chip is shown in Fig. 2. The VLM operates by vaporizing a suitable liquid propellant inside a micro-machined, thin-film deposited heater. Water, ammonia, and

hydrazine are currently under consideration as propellants, although in principle any propellant that can be vaporized, and does not exhibit compatibility issues with the materials of construction, may be used. As a result of the microfabrication techniques employed in its fabrication, extremely small thruster size and weights can be achieved. Chip weight is a few grams, and current chip sizes are about $0.9 \times 1.5 \times 0.1$ cm^3, with a slightly smaller version of $1 \times 1.1 \times 0.1$ cm^3 currently under construction. Thrust and impulse bit values have not been measured yet at this stage of the development, however, targeted performance data for the VLM are thrust values of 1 to several mN or less and impulse bit values of 10^{-6} to 10^{-5} Ns (depending on available valve technology). Input power levels and voltage bus requirements have to be minimized to take into account limited onboard power levels and the trend towards low bus voltages on microspacecraft. Vaporization of propellant (water) has been achieved at power levels around 2 W and voltages of slightly under 2 V.

The VLM concept appears attractive for microspacecraft attitude control for a variety of reasons, some of which have already been alluded to above. While some of these are related to the microfabrication techniques used in VLM construction, others are unique to this concept. Specifically, these are:

(1) *Small size and weight:* As indicated above, using microfabrication technologies such as MEMS, allows for an unprecedented degree of thruster miniaturization. This fact is of particular importance for microspacecraft attitude control. Three-axis stabilization, depending on spacecraft configuration and propulsion system layout, may require as many as one dozen thrusters. For spacecraft the size of a "grapefruit" to "basket ball", weight and space are at a premium, and microfabricated thrusters bear obvious advantages for such applications. However, even larger spacecraft will naturally benefit from volume and mass reductions achieved in the propulsion system.

(2) *High achievable level of integration:* It has been argued within the micropropulsion community, and rightfully so, that while MEMS-based thruster chips may achieve unprecedented degrees of miniaturization, weight and volume savings of a fully packaged MEMS-thruster (consisting of the chip, a metal casing protecting the chip, and propellant and electrical interfaces) may be limited when compared with more conventional metal fabrication-based microthruster technologies. However, MEMS technologies potentially allow of an extreme level of integration between thrusters, such as the VLM, and other MEMS-based propulsion components, such as valves and filters, for example, through direct chip-to-chip bonding. Even necessary control or power conditioning electronics maybe directly integrated onto the thruster or valve chips. The bonded structures could then be packaged into extremely compact, modular feed system units with minimal external interfaces, consisting of a propellant inlet and several leads for power supply and command and control. Integration of these

units into microspacecraft, as well as larger scale spacecraft, would be easier and less costly than using conventional propulsion system architectures, and dry weight and volume savings of a system based on such unites could be significant.

Such highly integrated micropropulsion systems would also lend themselves for use in distributed propulsion system architectures. Here, propulsion modules consisting of thrusters, feed system components, and tanks would be placed around the spacecraft bus wherever they may be needed. Again, integration of the propulsion system into the spacecraft would be simplified, since no propellant feed line routing from a central tank and propellant management system to remote thruster locations would be required. This simplification will be of particular significance in microspacecraft, where the routing of fragile, miniature propellant lines in tightly configured spaces could become very complex. In order for such an approach to be sensible, however, dry masses of the individual modules will need to be extremely low. The VLM thruster chip concept, among other microfabricated propulsion components on a chip[6], may represent such an ultra light-weight approach.

(3) *Small impulse bit and high thrust-to-power ratio:* Very small impulse bits, as low as 1 - 50 μNs, will be required for microspacecraft attitude control as well as interferometry missions. As alluded to above, the use of MEMS technologies will allow for the fabrication of extremely small nozzle throat diameters, resulting in small thrust levels and, providing the availability of sufficiently fast actuating valves, small impulse bits. The VLM thruster in its current design stage features nozzle throats as small as 50 μm square. Even smaller dimensions are possible without significant additional effort. A VLM thruster that is sized to deliver thrust levels on the order of 0.1 - 1 mN, featuring a valve with an actuation cycle of 1 - 10 ms, would be able to deliver the desired small impulse bits.

However, attitude control thrusters may be required to fulfill multiple functions, such as slew maneuvers in addition to pointing and deadband control. It is common onboard state-of-the art, larger scale spacecraft to use the same attitude control system for both functions to reduce dry weight and cost of the propulsion system. For these reasons it certainly has to be expected that microspacecraft propulsion systems should have the ability to fulfill multiple tasks as well given the even more stringent volume and mass constraints to be anticipated for these spacecraft. Since the VLM is an electrothermal thruster concept, larger thrust-to-power ratios are to be expected for this thruster type than for electrostatic or electromagnetic types, potentially resulting in lower power requirements for a given thrust during slew maneuvers than are obtainable with FEEP or PPT thrusters, for example. While there will certainly be cases where required slew rates may be low enough to allow for lower

thrust-to-power options, it appears reasonable to assume that many microspacecraft missions will benefit from high thrust-to-power options.

(4) *Reduced leakage concerns*: The VLM is a phase-change thruster concept that vaporizes propellant, stored compactly in its liquid phase, on demand. Using liquid, rather than gaseous propellants, reduces leakage concerns commonly found in high-pressure cold gas systems. In addition, liquid propellants allow for more compact storage. Both issues weigh particularly heavily in view of microspacecraft applications since these craft will be severely mass and volume constraint, and will not be able to afford substantial propellant leak rates due to the limited onboard propellant supply.

(5) *Flexibility of propellant use*: In principle, the VLM may use any propellant that can be vaporized. In current laboratory testing, water is being used for safety and ease-of-handling reasons. Ammonia will yield higher performances in terms of power requirements and efficiency due to a heat of vaporization approximately half that of water. Other propellants, such as hydrazine, due to its considerable flight heritage, may be considered pending compatibility investigations of this propellant with materials used in thruster construction. Propellants may be selected to provide the least amount of contamination or interference with onboard science experiments.

(6) *Simplicity of design*:: The VLM thruster is characterized by the simplicity of its design. It does not contain any moving parts, such as pumps or turbines, nor does it rely on combustion or plasma generation processes, which may be difficult to sustain in very small thrust chamber volumes. The result of this approach maybe increased reliability and higher chance of success in the development phase of the VLM concept, at the expense of reduced performance over combustion-based or electric thruster concepts with respect to thrust and specific impulse, respectively. However, high performance in neither category is required for most attitude control applications.

Obviously, the concept of heating a working fluid in a heat exchanger element and expelling it to produce thrust is not new and has been exploited in resistojet designs for many years, although many of these designs have employed gaseous propellants[7]. The uniqueness, and challenge, of the VLM lies in adapting this concept, using liquid propellants for compact propellant storage and reduced leakage rates, and employing it to microscale devices featuring heater lengths no more than a few millimeter in length. Until the successfully completion of experiments to be discussed in this paper, it was not certain whether vaporization of propellant could be achieved over such short distances. Currently, similar work on a microfabricated resistojet is also being performed at the Aerospace Corporation[8].

Sometimes the VLM concept is being compared with inkjet printer head technology, however, upon closer inspection the VLM concept is quite different from inkjet technology. Even though the conception of the VLM took its roots in considerations related to the potential use of inkjet technologies for microspacecraft thruster use[9], only some generic design approaches, such as general microfabrication and thin-film deposition techniques have survived in the VLM design. The obvious differences between the inkjet and the VLM thruster lie in the intended composition of its exhaust products. While in the inkjet a liquid droplet is to be expelled, complete vaporization of the propellant is essential for the VLM to be successful as a thruster. Droplet velocities found for inkjets are far too low (corresponding to approximately 1-2 sec specific impulse)[10] to be of interest in space applications.

Liquid droplet formation is achieved in an inkjet printer head by filling a cavity with liquid ink[10-13]. One side of the cavity is occupied by a 50 to 100 μm square heater element. Upon actuating the heater, a bubble forms adjacent to the heater element. The bubble expands into the liquid reservoir, pushing liquid ink ahead of its expanding boundary and forcing a liquid ink droplet out of the inkjet nozzle. In the VLM design, on the other hand, in order to avoid liquid droplet ejection, the inkjet cavity has been replaced by an elongated channel, featuring several millimeter long heater elements deposited on two opposite channel walls. Heating is initiated prior to liquid injection to ensure complete vaporization of all the propellant before it exits the channel through a nozzle at the downstream end of the channel.

Significant progress was made recently in the development of the VLM by successfully demonstrating the ability of this thruster concept to completely vaporize propellant (water) over chip length scales. In the following chapters, chip design and fabrication, thermal characterization of the chips, as described by the power required to obtain a certain chip temperature, as well as initial flow and vaporization tests using thruster chips featuring different heater designs will be described.

III. VLM DESIGN

The VLM concept consists of a laminate of three chips, as seen in Fig. 3. The top and bottom chips contain the vapor deposited thin-film heaters, as well as the nozzle and inlet. Also featured on these chips are two vias to electrically contact the heater elements. These wafers are bonded into a stack via a spacer, or channel, chip. This channel chip features a cut-out that forms the sidewalls of the flow channel as well as vias needed to contact the lower heater element, since electrical contacts are only made from one side of the chip. The cut-out forming the flow channel walls was fabricated

using a state-of-the-art Deep Trench Reactive Ion Etching (RIE) technique that allows straight channel walls to be formed, in contrast to the anisotropically etched, angled nozzle and via walls.

Flow entering the chip through the inlet will enter the flow channel formed by the two heater sections and the spacer, be vaporized through heat transfer from the heater elements, and then exit the nozzle in a gaseous state. The channel has a width of 0.95 mm. Channel height is determined by the thickness of the spacer wafer. In some cases, a full-thickness spacer wafer was used, resulting in a channel height of 0.6 mm. In others, the spacer wafer was etched back to a thickness of 0.3 mm, leading to a channel height of the same dimension. As will be seen below, the flatter channel profile results in more complete vaporization of the propellant due to the fact that the surface to volume ratio was increased by this design change.

Channel inlet and nozzle are square-shaped following the anisotropic etch patterns of 100-silicon wafers and have throat dimensions of 50 x 50 μm^2. The nozzle is symmetric with respect to its converging and diverging sections and since the silicon wafer into which the nozzle was machined is 0.6 mm thick, length of the diverging (and converging) nozzle section is 0.3 mm. It should be noted that this current nozzle shape is merely a place holder for more optimized nozzle contours to be integrated into future version of the VLM. Currently, optimized nozzle contours are being investigated under a JPL contract at MIT[14, 15].

The three wafers making up the VLM chip are bonded via a thin gold layer through a metal-to-metal thermal compression process. This has the advantage that the bonding medium as well as the heater elements, also formed through the deposition of a gold layer, can be processed in the same fabrication step. Gold is being used as heater material since its low resistance will result in low voltage requirements for the thruster. One set of chips was designed featuring polysilicon heaters for comparison. Polysilicon heaters would be required if in future versions of the VLM the silicon wafers were to be fusion bonded, rather than thermal compresson bonded. Fusion bond strengths are believed to be much stronger than thermal gold compression bonds. However, fusion bonding does require a high temperature (900 - 1000 C) annealing step, which would not allow gold heaters to be used.

In past design iterations, Pyrex material was intended for use as the the spacer wafer material, to be bonded anodically to the silicon nozzle and inlet wafers[4,5]. This Pyrex-silicon anodic bond also features high bond strengths[4], however, does not require a high temperature anneal as in case of a fusion bond. However, it was noted during the fabrication of the Pyrex spacer, requiring ultrasonic

machining processes to form the channel and vias, that unacceptable surface roughnesses had appeared on one side of the wafer, preventing successful bonding. The surface roughness was not found to be homogenous across the wafer surface, but only appeared in certain regions of the wafer, distributed in a regular pattern. It appeared that an abrasive slurry, used during the ultrasonic machining process, had caused abrasions in the antinode regions of the vibrating spacer, with the spacer vibrations being caused by the ultrasonic tool. Subsequent polishing attempts of the Pyrex spacer failed and led to repeated wafer breakage, likely due to internal stresses caused by a combination of drilling of a multitude of holes per wafer (more than a dozen VLM spacers were fabricated per 3" dia. Pyrex wafer) and the thinness of the wafer (0.5 mm). Repeated attempts by the vendor to deliver a satisfactory product failed and, finally, this technique was abandoned in favor of the gold compression bonding technique.

Another design detail can be seen in Fig. 3 when inspecting the top heater chip. Just opposite the heater strip a recess was machined into the silicon substrate, thinning the substrate material at this location. The purpose of this design feature was to provide a thermal choke to reduce heat conduction from the heater surface to the remainder of the chip. Wallace[4] had previously calculated an approximately five-fold reduction in conductive heat losses for a 1000 μm wide recess leaving a 100 μm thick silicon membrane when compared with a plane substrate. However, in order to simplify fabrication, the recess only extended about 300 μm deep into the 600 μm silicon substrate wafer, thus leaving a 300 μm silicon membrane. This allowed the recess to be manufactured in the same process step as the nozzle and inlet. Unfortunately, at this large a thickness the thermal choke proved rather ineffective, as will be seen in Section IV, and the design will be changed in future versions of the chip.

The chips were packaged by placing it into a ceramic (alumina) hybrid chip carrier with a port drilled into the bed for access to the chip inlet. This carrier provided both electrical as well as propellant interfaces. Bonding of the chip to the carrier was facilitated by a high temperature epoxy. A threaded nut (aluminum or Vespel) with a central through hole was bonded to the bottom of the chip carrier, with the through hole overlapping the port drilled into the carrier and the chip inlet. This nut will allow the packaged chip to be plumbed to a feed system providing the propellant. It should be noted that this packaging scheme serves initial bench top tests aimed at preliminary characterization of thruster chip performance only. It has the advantage of being cheap and consists of readily available commercial components. Thruster packages more closely resembling flight hardware will likely require customized packaging.

In the following, a first set of VLM experiments will be described. These tests included thermal characterization tests of the chip, determining power and voltage requirements versus heater temperature, and a proof-of-concept test of the VLM using water propellant, demonstrating, for the first time, that complete propellant vaporization is possible with a VLM.

IV. THERMAL CHARACTERIZATION

Description of Experiment

Available power onboard a microspacecraft may be severely limited, potentially not exceeding a few tens of Watts for the total spacecraft. Thus, any micro-thruster concept to be used on a microspacecraft will be required to operate within potentially considerable power constraints. In the case of the VLM, sufficient heater temperatures will have to be attained within these constraints to achieve complete propellant vaporization. Thus, a thermal characterization of the chip, i.e. the measurement of heater temperature vs. input power, is a critical evaluation criterion in the applicability of the VLM to microspacecraft use. Similarly, bus voltages onboard microspacecraft may be significantly lower than common on spacecraft today, possibly as low as 5 V. Thus, any microthruster should be able to meet these requirements and, consequently, required thruster voltages were recorded as well during this experiment.

In order to perform the temperature measurements the chip was placed under an infrared (IR) camera and power supplied to the chip was measured for a given chip temperature. The thruster temperature could only be measured on the outside walls of the chip and a position in the recess area, just opposite one of the heater elements (compare with Fig. 1), was chosen as a location for the IR camera to lock on. A small dot of black graphite-based paint was applied to the chip at this location to provide a surface of well characterized emmissivity for the IR camera. Due to the temperature measurement location, actual heater temperatures may have been slightly higher as a temperature drop may have occured across the 300 μm thick silicon membrane separating the heater element from the actual measurement position. However, given rather small silicon substrate thickness differences are believed to be small.

Tests were performed with a chip featuring a 4 mm long gold heater, packaged as described above. Although an aluminum or Vespel nut, respectively, was bonded to the chip carrier in these measurements, the nut was not connected to a feed system. All initial tests were performed without

water vaporization occurring inside the chip to check the thermal design of the chip independent of the vaporization processes and power requirements associated with them.

Results

Results of the thermal characterization of the packaged chip are shown in Figs. 4 and 5 representing electric input power and voltage data vs. heater temperature. In the case where an aluminum nut was used, approximately 3.5 W were required for a chip temperature of 100 C, about 5.5 W for 150 C and 7.5 W to achieve 200 C. The maximum chip temperature of 254 C was reached at 8.5 W after which the test was terminated voluntarily. Voltage requirements were approximately 3.7 V at 100 C, 4.5 V at 150 C and reach 5.4 V at 200 C.

During the tests it was noted that despite the ceramic chip carrier being placed between the chip and the aluminum nut, the nut got very hot, obviously acting as a heat sink for a considerable amount of the energy provided to the chip. Thus, a nut made from Vespel was bonded to the chip carrier to investigate how such a relatively simple design change would impact chip performance. As Fig. 4 indicates, required chip power levels, and thus voltages, could be lowered significantly below the case using the aluminum fixture. At 100 C, the required power level and voltage was 2.3 W and 2.6 V, respectively. The corresponding values at 150 C were 3.6 W and 3.4 V, and at 200 C they were 5 W and about 4.3 V. This corresponds to a drop in electrical input power at the same chip temperature of about 35 % in the case of a Vespel versus an aluminum nut and required voltages could be kept well below 5 V for the vespel package, even in the cases of the highest temperatures, thus demonstrating the dramatic role that proper chip packaging will play in the future.

Further design changes are anticipated to improve the obtained results. During the tests described above it was noted that, by placing multiple graphite paint dots onto the chip surface at various locations to measure the temperature there, the temperature profile across the chip surface was rather uniform. Ideally, a peaked temperature distribution is desired, with maximum temperatures occurring in the recess areas. Obviously, the 300 μm deep recess, leaving a 300 μm thick silicon membrane, was rather ineffective. A new chip is currently under construction with a thinner silicon membrane (100 μm) which should improve the thermal choke and lower the temperatures of the chip near its interface areas, thus reducing heat losses. This new generation of VLM chips will also feature a smaller footprint, aimed at reducing heat conduction losses further by reducing the interface area between chip and carrier by 20%.

V. PROOF-OF-CONCEPT

Experiment

It is important to achieve complete vaporization inside the thruster since droplet nozzle exit velocities are slow by comparison with gaseous ejections and would thus significantly lower the specific impulse and result in inefficient use of propellant. Achieving this goal with the VLM poses a major challenge as vaporization has to be accomplished over very small heater lengths (on the order of a few millimeter) in order to be compatible with typical chip dimensions, while, at the same time, power requirements have to be kept low. Power values of 5 W or less were targeted. Achieving these goals was by no means certain at the outset of this project and a proof-of-concept demonstration of the VLM was thus considered a crucial milestone.

Using several packaged chips, propellant vaporization tests were conducted. The chips were mounted onto a test rig consisting of a water tank, a 2-micron filter placed at the tank outlet, and a small commercial solenoid valve manufactured by the Lee Company. The packaged chip assembly was mounted onto a port via the already mentioned threaded aluminum or Vespel nuts bonded to the chip carrier (see Fig. 6). A pressurant supply was connected to the water tank. By pressurizing the tank, water is forced through the filter and valve and into the chip. In early tests, feed pressures had to be lowered below 1 psig to adjust water flow to levels low enough to achieve vaporization. In these cases, the pressurant supply was replaced by an additional water tank placed at an elevated position above the chip assembly and the propellant was gravity-fed.

Different chip configurations were tested, listed in Table 1. They included two chips featuring 4 mm heater lengths with a channel cross section of 950 x 600 μm^2, as well as chips with a narrower channel cross section of 950 x 300 μm^2 and channel lengths of 5 and 6 mm, respectively. Heater widths in all cases were 650 μm, i.e. slightly narrower than the channel width. This is necessary to avoid electrical contact between the gold heater and the gold layer acting as bonding agent between the various wafers making up the VLM chip. One chip featured a polysilicon heater to study operating differences between this heater material and gold.

Finally, one chip featuring a meandering channel layout with a channel height of 300 μm and channel width of 400 μm, as shown in Fig. 7, was fabricated. As a result of the meandering path, total channel length is 12.16 mm. This meandering flow path is attained by modifying the fabrication

of the center spacer wafer of the VLM. Rather than machining an ordinary straight cut-out in the center spacer wafer of the VLM chip (compare with Fig. 3), equidistantly spaced silicon fins of a width of 100 μm, protruding 550 μm out from the side-walls of the cut-out, are machined by appropriately altering the masks used in the etching process. The heater elements in the case of this particular chip are 5 mm long and 650 μm wide, i.e. remain rectangular in shape an extend below the fins. Since silicon is an excellent heat conductor, these fins are thus being heated through direct conatct with the heater elements and serve as additional heating surfaces for the flow entering the meandering channel.

A chip with a 4 mm straight channel, and a second chip with a meandering channel, yet more closely spaced fins, were also machined, however, were not able to flow any water. This may have been due to contamination inside the channels, blocking the flow, either acquired during handling of the chips during testing, or during the epoxy-bonding process when packaging the chips. It had been noted prior in a related project that epoxy, in a liquid phase during the bonding process, may flow into narrow channel sections due to capillary forces.

Procedure

A simple test procedure was followed in this first set of preliminary bench top experiments. The feed pressure was adjusted to a given level, and water was fed into the chip. The exit flow out of the chip was observed visually. Depending on the flow rate, which was not measurable in this first set of experiments due to the lack of suitable diagnostics, either a water jet (see Fig. 6), or a droplet forming at the nozzle exit was observed. When increasing the heater power, first an increase in water jet temperature was noted. At somewhat higher power levels intermittent vapor and liquid water ejections were observed, accompanied by a sputtering noise. Increasing power further finally led to the ejection of steam which could not be observed directly and could only be evidenced by observing its condensates on a mirror or glass slide placed into the vapor jet. At power levels still not quite high enough, vapor emission lasted only for a few seconds. Cooling of the chip then again led to the emission of liquid water. Cooling of the chip was evidenced by observing a shift towards lower voltage and higher current levels during propellant flow, indicating a decrease in resistance with lower heater temperatures. Finally, increasing the power level still further, continuous vapor ejection was observed using the already described glass slides or mirror surfaces. The tests were then repeated at a different feed pressure.

Results

Results obtained with the chips listed in Table 1 are shown in Figs. 8 and 9. Note that since flow rate measurements were not possible, data are plotted versus certain feed pressures. Obviously, considering the different channel designs, the same feed pressure may result in different flow rates for different chips. Thus it should be noted that a quantitative comparison between the different chip designs is not yet possible. Nonetheless, despite these limitations, a number of valuable observations could be made and are detailed in the following.

The first tests, conducted using chips featuring a 600 μm channel height, resulted in relatively high required power levels at extremely low feed pressures to achieve vaporization. The first successful vaporization tests conducted with the VLM required 7 W at about 0.25 psig feed pressure[5]. This data point is shown in the upper left hand corner of Fig 8. This chip featured an aluminum nut, which had been identified as a major heat sink due to the poor insulation provided by the ceramic carrier package. Replacing the aluminum nut with one machined out of Vespel material reduced required power levels by about 30% to just under 5 W at the same feed pressure. Using this chip assembly, vaporization was still possible at a feed pressure more than twice that value (0.64 psig) at about 6.5 W. However, even in this case power levels were still approaching or exceeding the maximum targeted value (5W), and, under vaporization conditions, only very low feed pressures could be maintained and, consequently, only extremely low flow rates could be achieved (although the latter could not be measured, when turning off the heater to observe purely liquid rates, only a small droplet could be seen forming at the nozzle outlet). In addition, vaporization was noted to be poor, and certainly not complete, as was evidenced by a continuous sputtering noise and frequent visible liquid droplet ejections in addition to the steam generated.

The low required feed pressures were not expected. As a major concern in the development of the VLM had been anticipated high viscous losses, in particular in the case of liquid propellant flow. Consequently channel geometries had been chosen conservatively large to accommodate the flow without encountering excessive flow resistances. This concern could clearly be dismissed after the described first set of tests. Thus, new VLM designs were fabricated and tested. These new chips featured lower channel profiles with a height of 300 μm. The goal was to bring more liquid into more immediate contact with the heaters and thus effect a more efficient heat transfer.

Using the new chips, a significant improvement in performance could be noted. In contrast to tests conducted with chips featuring 600 μm channel heights, vaporization was, once a critical power level had been attained for a given feed pressure, complete. Exhaust was invisible and could only be

evidenced by a cool glass slide placed into the vapor jet. No sputtering noises were heard. The critical power levels required to attain these conditions were also significantly lower as in earlier tests. For a chip featuring a 6 mm long heater, required power levels were only 2.3 W at about 1.3 psig feed pressure, increasing to 2.8 W at 5 psig feed pressure and 3 W at 10 psig feed pressure. These feed pressure values are within the realm of practical applicability, even for use in space hardware, and power levels are well below the initially targeted value. In addition, voltage requirements in this case range just below or above 2 V, depending on feed pressure, and are thus well within the capability of future microspacecraft.

Other chips featuring the same flatter channel profile (300 µm) resulted in somewhat higher power and voltage levels. In the case of a 5 mm heater, power levels were found to be somehwat higher, but are still well within the design targets, with the exception of one data point at a 10 psig feed pressure, in which case power requirements exceeded 8 W. This rather dramatic increase in power requirement with increased feed pressure (thus flow rate) for chips with shorter heater elements is reasonable, since less heat transfer to the liquid can occur over shorter heater lengths, requiring higher heater temperatures and power levels to result in complete vaporization. However, even for this chip no more than 5 V were required.

In the case of the meandering channel design, superimposed on a 5 mm long heater element, required power levels are higher than in the 6-mm long heater design even though the flow path in the meandering channel design is less than half as wide and twice as long as in the 6-mm long straight channel design. This appears surprising, however, as noted above, due to the lack of suitable flow rate measurements a direct quantitative comparison between the different chip designs was not yet possible. Despite this lack of accurate flow measurements it was noted, however, that the meandering channel design flowed considerable more liquid than the straight channel sections. While all other chips, even at the highest feed pressures, only formed a liquid droplet at the nozzle outlet in the unheated state, the meandering chip design emitted a water jet, similar to the one shown in Fig. 6. While this in itself is surprising, since higher flow resistance should have been expected in the meandering chip design, it does explain - qualitatively - the observed difference in required heater powers.

Possible explanations for these differences in flow behavior for the different chips could be contamination located inside the narrow flow channels, accumulated during handling and testing or through capillary-fed epoxy flow into the channel sections during bonding, or poor alignment between the various vias in the different chip wafers and the ports machined into the carriers and

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connecting nuts. In all cases, actual flow rates may be altered for a given feed pressure due to locally decreased flow cross sections. So far, evidence of contamination during handling and testing may have been found in the case of one chip which seized conducting liquid during tests. The same chip featured a misalignment between the port machined into the chip carrier and the chip inlet hole, the chip carrier surface partly covering the latter. In addition, one chip did not flow liquid at all, and contamination, if any, may have occurred prior to testing, possibly at some stage during the packaging phase, were chips leave the clean room environment. Once packaging is complete, chips are sealed in containers and not exposed to the environment prior to testing. Neither one of the failed chips is listed in Table 1 or Figs. 8 and 9, respectively.

Finally, a chip using a polysiliocn heater was tested. This chip again featured a straight channel and a 5 mm long heater. When comparing power requirements of this chip with a chip featuring a 5-mm gold heater, they can be found to be very similar in both cases for similar feed pressures, as would be expected. However, when examining Fig. 9, it can be seen that at these power levels the polysiliocn chip has voltage requirements well exceeding those of the gold heater by more thna a factor of two, i.e. approximately 5 V vs. 2 V in case of the gold heater. These differences in voltage requirements are expected to be critical in view of microspacecraft applications.

Lessons Learned

Despite this very preliminary data base obtained in this first set of bench-top experiments, several lessons could be learned from these tests that will benefit future work, such as

(1) The VLM concept was proven to be feasible. While future, more quantitative performance characterization is required and pending the availability of suitable diagnostics, it could be successfully shown that vaporization over chip length scales is possible within the power constraints and bus voltage levels expected to be found on microspacecraft.

(2) The value of shallower channel profiles, allowing more immediate heat transfer between the heater and liquid propellant has been demonstrated. Even at visibly higher flow rates, as discussed above, complete vaporization at lower power levels could be observed were chips featuring larger channel cross sections only delivered intermittent vaporization. Obviously, pending accurate flow rate measurements, this assertion needs to be quantified.

(3) Viscous flow losses, at least for the channel geometries encountered during these tests (950 x 300 μm^2 channel cross sections over channel lengths of several millimeters and flow orifices of 50 x 50

μm^2) are not very significant. Water can flow at rates exceeding the ability of the VLM to completely vaporize the propellant at acceptable power levels. However, flow rates will need to be measured to reach more quantitative conclusions

(4) Gold heaters are clearly preferred when considering VLMs for microspacecraft use where only very low bus voltages may be available. For use on larger spacecraft, this may not be a critical design issue.

(5) There exists a need for improved contamination control during the test phase. Although a 2-micron filter was placed into the feed line separating the tank and miniature solenoid valve, there appears to exist some evidence that blocking of flow passages may have occurred.

(6) There exists some very preliminary evidence that longer channels appear to perform better in terms of power requirements to achieve complete vaporization with increasing flow rates than shorter channel sections, as can be seen by comparing the 5 mm heater case with the 6 mm case. This is , of course, not unexpected. Again, a direct quantitative comparison between these two cases is not possible as flow rates may have been different in both cases and this statement thus requires further, quantitative confirmation.

Future Work

Given the constraints placed on this first set of proof-of-concept experiments, the need for future work to improve the existing, very preliminary data is strikingly evident. First, methods have to be found, or newly devised, to measure extremely low liquid flow rates. The case of measuring liquid rates is made difficult by the fact that, unlike in the measurement of gaseous flow rates, much smaller volume displacements are encountered for a given mass flow rate. In the case of the VLM, flow rates of 0.5 mg/s or less are being targeted.

Secondly, vacuum testing will need to be performed. Exposure to vacuum will likely reduce power requirements to achieve complete vaporization further. Pending suitable flow diagnostics, and using existing thrust stand hardware, detailed performance measurements will also need to be performed at this stage.

Thirdly, new VLM chip designs will need to be continuously introduced based on the latest findings. Currently, a new generation of chips is being fabricated incorporating design improvements

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already explored, such as shallower channels, in addition to featuring a smaller foot print and a deeper recess opposite the heater elements, narrowing the thermal choke (compare with Fig. 1), both aimed at further reducing heat losses from the chip. At the time of thrust stand measurements, new nozzle shapes will also need to be integrated into the chip, replacing the current anisotropically etched, square shaped "place-holder" nozzle.

Further improvements in thruster performance with respect to thruster efficiency and size will require a significantly improved understanding of microchannel two-phase flow phenomena as encountered inside the chip. Currently, the state of knowledge in this area is poor. Existing literature in this area addresses some special cases, in many cases not considering two-phase flow phenomena at all. However, an improved understanding of micro-channel two-phase flow physics, to be achieved through both experimenal research and accompanying numerical simulations, is essential in designing improved VLM heater designs, offering the potential of lower power requirements or shortened vaporization channels, further decreasing chip sizes.

Finally, different propellants will need to be tested, in particular those having lower heat of vaporization than water, which should result in additional power reductions for achieving vaporization. At this stage, detailed propellant compatibility studies will be required, and, if needed, appropriate chip coating techniques need to be devised to avoid chip erosion. Other issues to be addressed will be concerns related to the dribble volume, formed by the heater channel volume downstream of the thruster valve, which may broaden the thruster impulse bit. Although longer channels may be beneficial for vaporization reasons, they will increase the dribble volume unless channel cross sections are constrained. This may lead to higher feed pressure requirements, which in view of the low feed pressures encountered so far could probably be accommodated. Last but not least, assuming that satisfactory performance of the VLM can be demonstrated, thruster integration with other feed system components as well as control electronics, on the same chip or through chip-to-chip bonding, will need to be addressed aggressively in order to reap one of the major benefits of a MEMS-based thruster over more conventional designs.

VI. CONCLUSIONS

The feasibility of a so called Vaporizing Liquid Micro-Thruster (VLM) concept was proven. This thruster concept relies on the vaporization of a liquid propellant in a thin film deposited, microfabricated heater arrangement. Use of liquid vs. gaseous propellants will significantly reduce leakage and propellant storage concerns for an operational device. The thruster chip, about 0.9 x 1.5 x 0.1 cm^3 in size and weighing but a few grams, was able to completely vaporize water propellant at

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power levels as low as 2 W and required voltages of merely 2 V for a 6 mm long heater at feed pressures of about 1.3 psig. At 10 psi feed pressures, the same chip achieved complete vaporization at 3 W and an only slightly increased voltage of 2.2V. Tests were conducted in a simple bench-top experiment and the water vapor was evidenced by observing condensates on a cool glass slide or mirror surface.

Different chip configurations were tested. Shorter heaters resulted in higher power requirements to achieve vaporization, however, power levels remain below the 5 W level in most cases and voltage requirements seldom exceeded 3 V. A quantitative comparison between different chips, however, is not yet possible due to non-existing diagnostic capabilities with respect to very low liquid mass flow rate measurements, as required for VLM characterization. Targeted mass flow rates for the VLM are 0.5 mg/s or less. Chip designs featuring flatter heater channel geometries, placing a greater portion of the liquid into more immediate contact with the heater elements, resulted in clearly improved vaporization at reduced power levels over chips featuring larger channel heights.

Thermal characterization of the thruster revealed that approximately 2.6 W are required to achieve a heater temperature of 100 C for a 4 mm long heater, 3.4 W to achieve 150 C, and about 4.3 W to reach 200 C. Chip temperatures were measured on outside surfaces of the chip using an infrared camera, and actual heater temperatures may have been slightly higher, taking into account conduction losses through a thickness of about 300 μm silicon separating heater and outside surfaces. Heat loss into the chip packaging structure was found to be significant as was determined by comparative testing of chips using aluminum interfacing fixtures and corresponding fixtures made from Vespel. The aluminum fixtures acting as significant heat sinks, despite being separated from the chip through a ceramic chip carrier, resulting in about 50% higher power consumption for the same chip temperature.

Viscous flow losses inside the chips were found to be small, even at channel cross sections of 950 x 300 μm^2 over several millimeter channel lengths, and featuring orifices at two locations as small as 50 x 50 μm^2. While initially thought to be a concern, flow resistances proved to be small, allowing adequate water flow rates for VLM operation. However, contamination control was identified as an area deserving greater attention in the future as there exits some evidence that flow passages in some chips may have been blocked either while handling them during testing or during packaging procedures.

It is clear from this first set of tests that substantial future work will be required in the development of the VLM. Data obtained to date is very preliminary and in many cases does not yet allow for a quantitative comparison between different chip designs. Most importantly, suitable flow diagnostic methods need to be investigated, or newly devised, to measure the low VLM liquid flow rates. Testing under vacuum conditions will follow. It is expected that power requirements to achieve complete vaporization under these conditions will be even lower than the ones reported in this study. Finally, a detailed performance characterization will be performed, requiring the determination of thrust levels and flow rates to determine specific impulse.

New chip designs will be fabricated throughout the program, incorporating the latest findings. One such design iteration currently in fabrication features a smaller chip footprint and a deep recess machined into the outside of the chip surfaces, just opposite the heater elements located on the inside of the chip. This will create a thermal choke and, combined with the smaller footprint of the chip, is anticipated to reduce heat losses from the chip for a given heater temperature. Eventually, the anisotropically etches, square shaped nozzle, currently acting as a place-holder for more sophisticated nozzle designs, will need to be replaced.

Finally, pending successful performance demonstrations, other issues will need to be addressed, such as the examination of propellants featuring lower heat of vaporization, for example, designed to reduce power requirements further, propellant compatibility studies between these and other propellants and the materials of chip construction, devising suitable chip coating techniques should propellant compatibility issues dictate such design changes, and VLM integration issues with other feed system components, such as filters and valves, or power conditioning and control electronics, either on the same chip or through direct chip-to-chip bonding. Pursuit of this latter issue will reap one of the major benefits a MEMS-based thruster concept may offer over more conventional technologies, i.e. the conception of tightly integrated, extremely compact thruster modules, likely not achievable with conventional approaches.

Thus, despite the admittingly preliminary data obtained for the VLM thruster so far, the results obtained to date are significant in that they demonstrate the feasibility of the concept, and point to the future capabilities to this new technology, vital for microspacecraft designs, and potentially of use to many other mission classes as well.

VII. ACKNOWLEDGMENTS

VIII. REFERENCES

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Table 1: VLM Chips Tested

Designation	Heater Length (mm)	Channel Cross Section (μm^2)	Channel Type	Fixture Material
SC-4-600-Al	4	950 x 600	Straight	Aluminum
SC-4-600-V	4	950 x 600	Straight	Vespel
SC-5-300-V	5	950 x 300	Straight	Vespel
SC-5-300-V/Poly*	5 (PolySi)	950 x 300	Straight	Vespel
SC-6-300-V	6	950 x 300	Straight	Vespel
MC-12--300-V	12.16	400 x 300	Meandering	Vespel

*featuring a heater made from polysilicon. All other heaters made from gold.
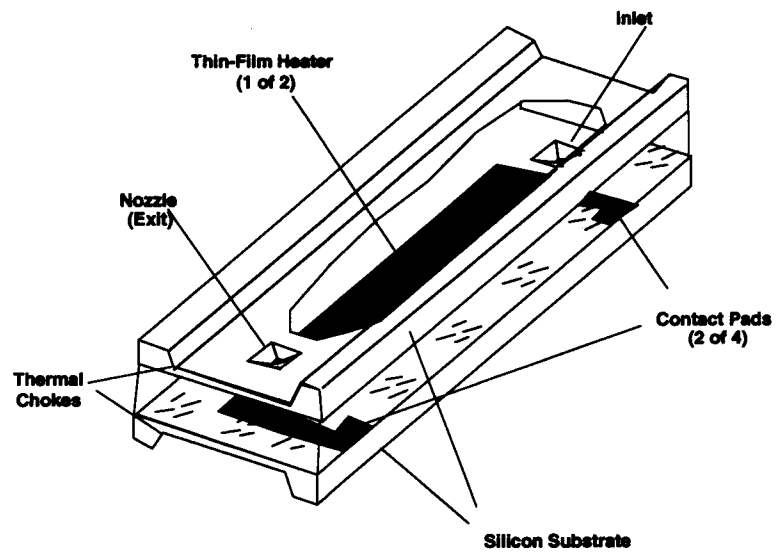
Fig. 1: Concept of the Vaporizing Liquid Micro-Thruster

Fig. 2: Vaporizing Liquid Micro-Thruster Chip
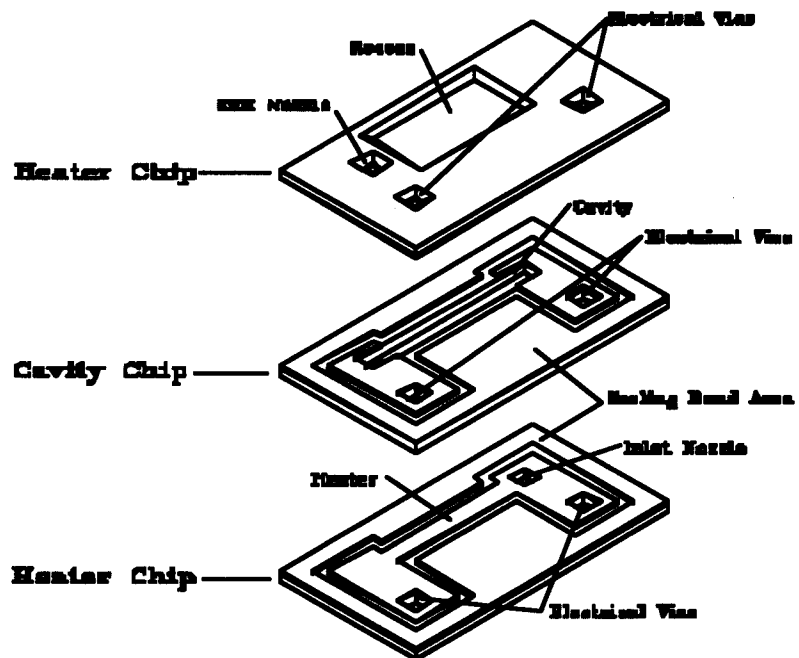
Fig. 3: VLM Chip Design Components
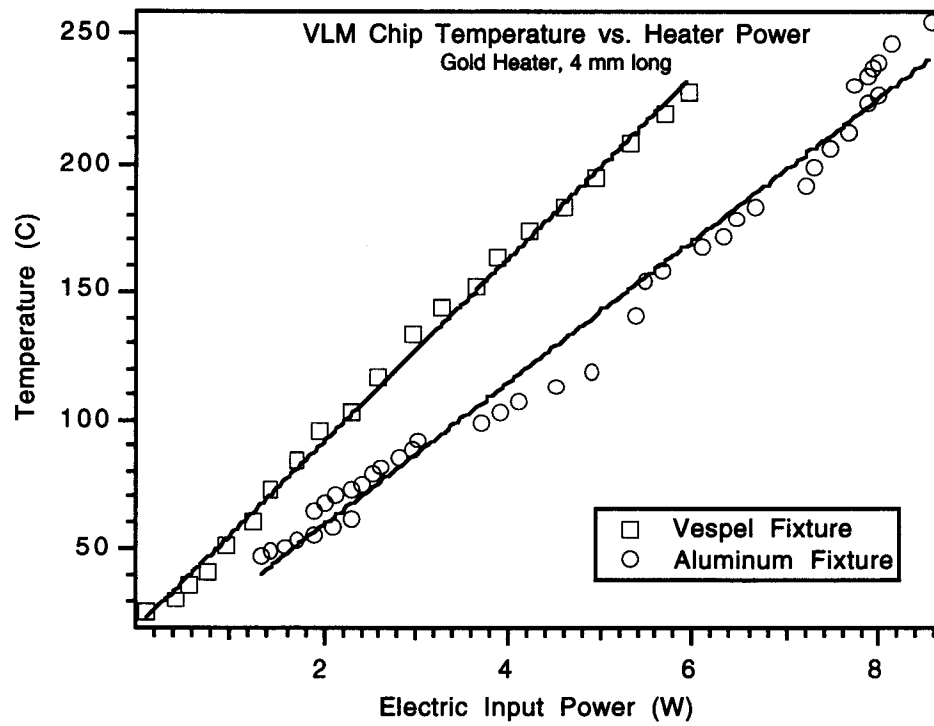
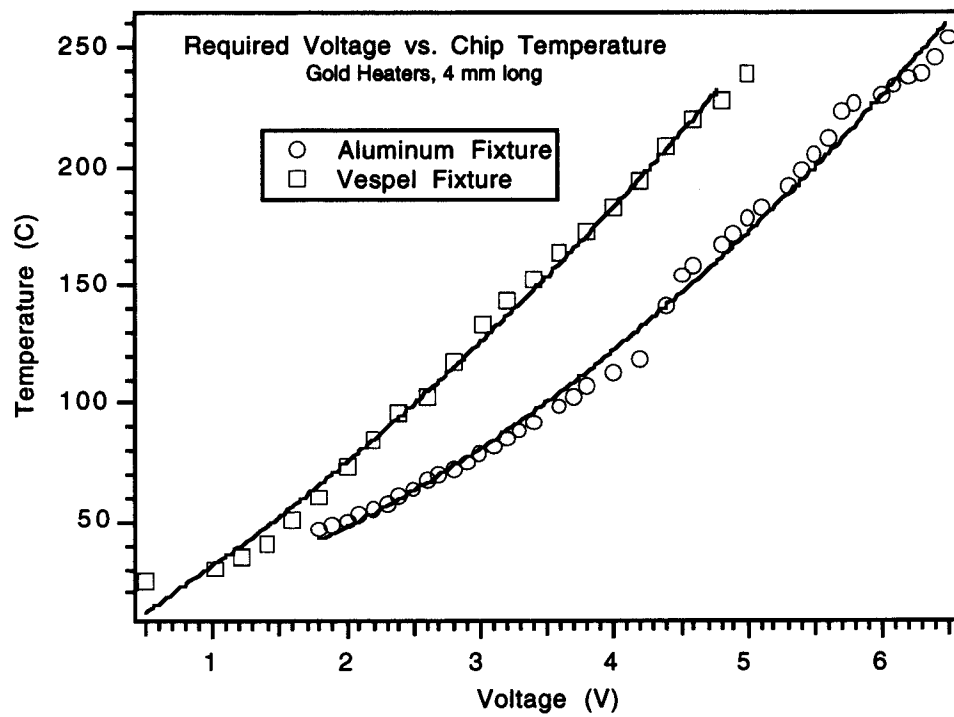Fig. 4: VLM Chip Temperature vs. Electric Input Power for Different Packaging
Approaches

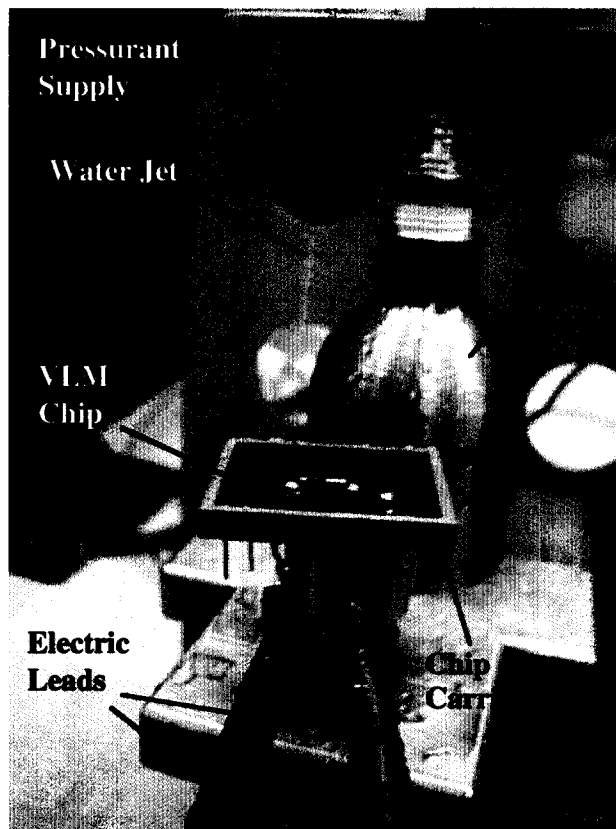Fig. 5: Chip Temperature vs. Voltage for Different Chip Packaging Approaches

Fig. 6: VLM Chip on Chip Carrier attached to Water Tank. Notice Water Jet Exciting Nozzle. No Heat Input to Chip.
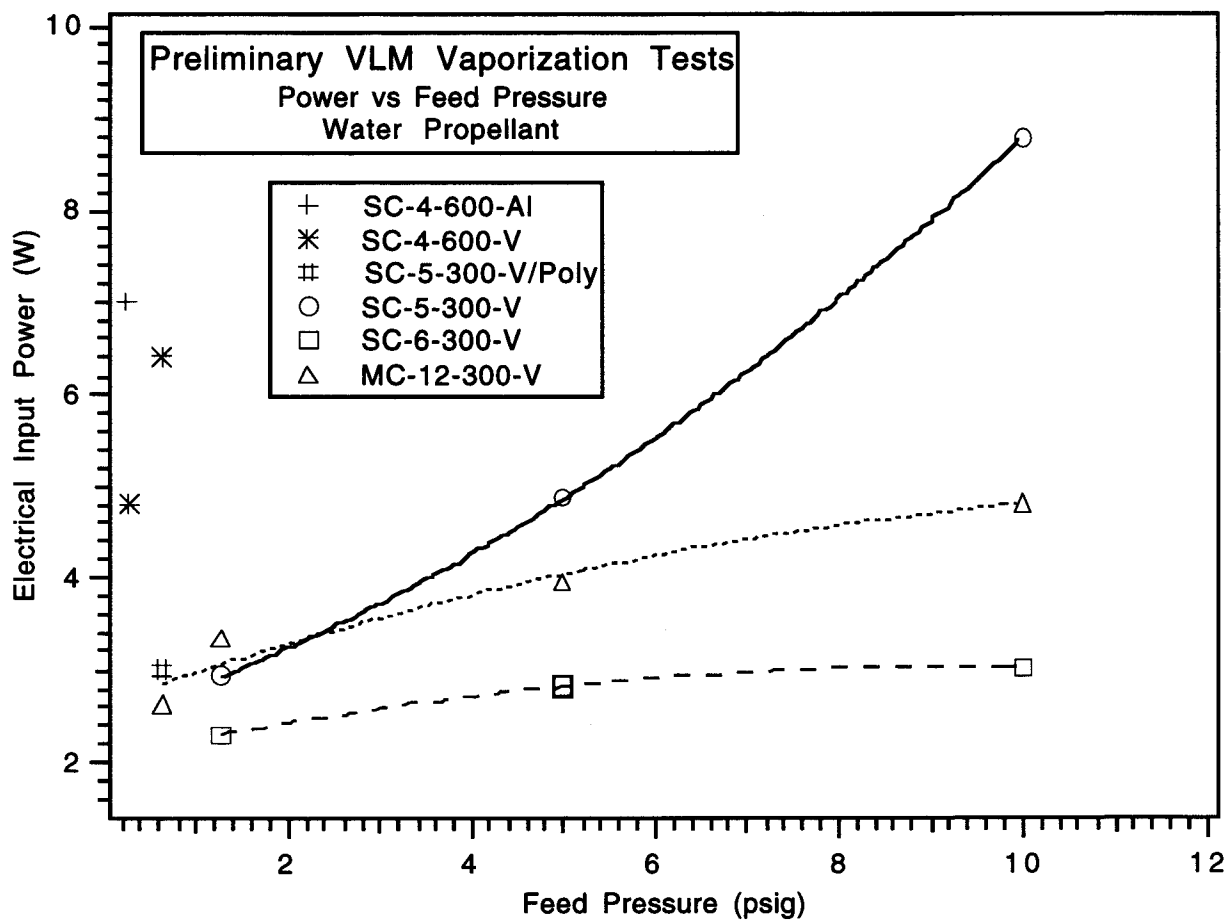
Fig. 7 in progress

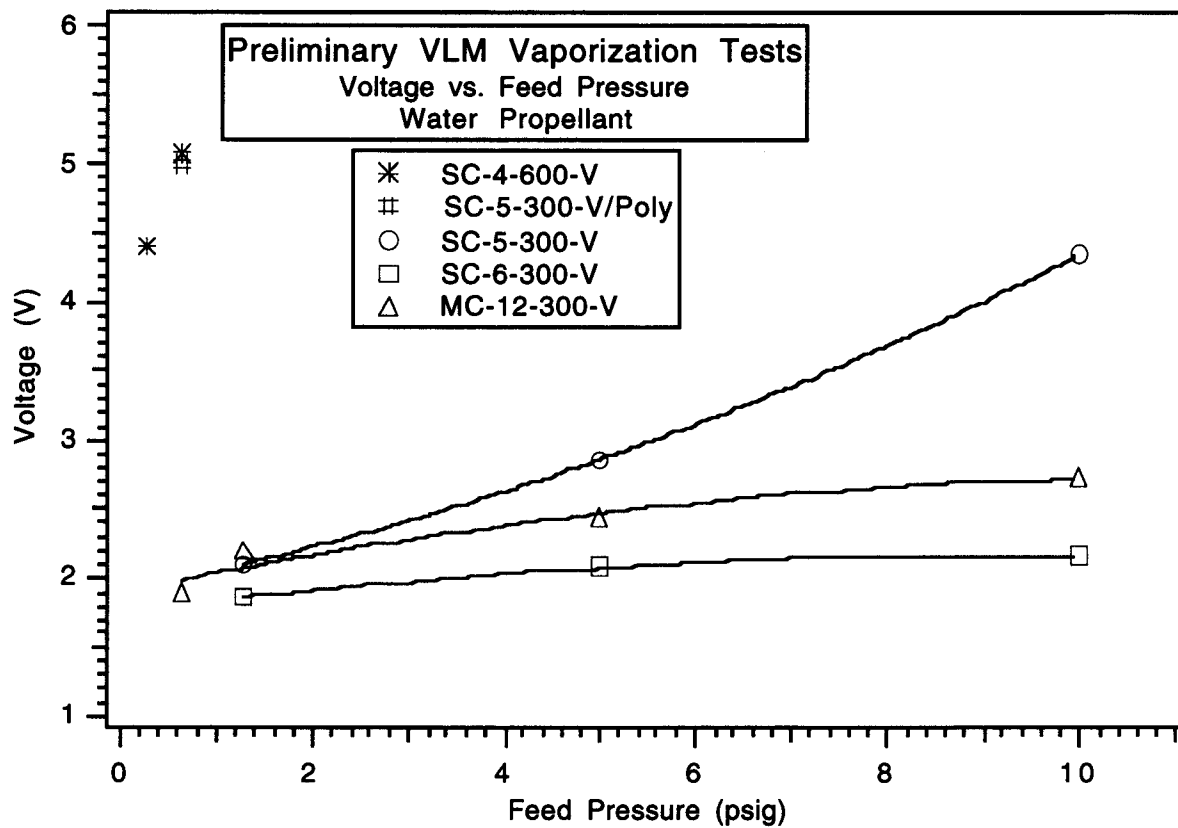Fig. 8: VLM Vaporization Tests (Power vs. Feed Pressure)

Fig. 9: VLM Vaporization Tests (Voltage vs. Feed Pressure)